Efficient optical gradient echoes as a quantum memory for light using two level atoms

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We propose a quantum memory for light based on the optical analog of an NMR gradient echo. The proposal is simpler than current quantum memory proposals using controlled inhomogeneous broadening. The proposal can achieve 100% efficiency with realistic parameters. It only requires two level atoms and no auxiliary light pulses are needed during storage and recall. We present an analytical treatment, numerical simulations and preliminary experimental results. Experimental efficiencies of 13% were achieved and we discuss the improvements needed to make this closer to unity.

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Some of the most significant advances in quantum information processing have been made using quantum optics-based techniques. To proceed further it is necessary to have devices such as single photon sources, quantum memories and quantum repeaters, where quantum information is exchanged in a controlled fashion between light fields and material systems. It has been proposed that both the required control and strong coupling can be readily achieved using an ensemble approach, where the light field interacts with a large number of identical atoms.

To date quantum states of light have been mapped onto, but not yet recalled from, atomic vapours using the resonant interaction of light with spin polarised cesium vapors [1]. Single photon states have been stored and retrieved from atomic ensembles using electromagnetically induced transparency [2, 3], although with poor efficiency.

In 2001 Moiseev and Kröll [4] published a proposal for a quantum memory for light based on modified photon echoes. In contrast to a normal photon echo, the required rephasing came from controlled reversible inhomogeneous broadening (CRIB) rather than from optical pulses. In the initial proposal the reversible inhomogeneous broadening used opposite propagation directions in a Doppler broadened medium. Since then the idea has been generalised to other broadening mechanisms [5, 6, 7].

A photon echo using reversible inhomogeneous broadening has been demonstrated using Stark shifts in europium dopants [8], as has the ability to store multiple pulses [9]. Work toward demonstrating such echoes in other systems has also been carried out. [6, 10, 11].

To date all the proposals for a quantum memory using CRIB operate via a time reversal of the storage process. Reversing the detunings of the atoms transforms the equations of motion for light travelling in the backward direction into a time reversed copy of that for light travelling in the forward direction. A pulse propagating in the forward direction is absorbed by the ensemble and then the detunings of the atoms are flipped and a phase matching operation is applied. After this the pulse exits the ensemble in the backward direction as a time reversed copy of what was applied. The phase matching operation consists of a pair of counter propagating π pulses driving the atoms from the excited state down to, and back up from, an auxiliary level.

Here we show that 100% is theoretically possible using only two level atoms and with the ouput pulse propagating in the same direction as the input pulse. It had been thought that such two level wouldn't be able to approach unit efficiency because of the problem of reabsorbtion. However this isn't the case if the inhomogeneous broadening is introduced in such a way that the detunings of the atoms is linear position. The principle benefit of such a two level scheme is its simplicity. It requires only two atomic levels which makes the scheme applicable to many more systems. In particular erbium dopants which allow operation at 1.5 μm, have been shown to have very good two level atoms [12] but a lambda system hasn't been demonstrated yet. The absence of phase matching π pulses greatly simplifies the implementation, it also means that the only light seen by the ensemble during the operation of the memory is the light that is stored and then re-emitted.

Here we consider the interaction of a collection of two level atoms with a light field where the detuning of the atoms is proportional to their position. The Maxwell-Bloch equations describing this process in the frame at the speed of light and after making the small pulse approximation are:

$$\frac{\partial}{\partial t}\alpha(z,t) = -i\eta z\alpha(z,t) + igE(z,t) \quad (1)$$

$$\frac{\partial}{\partial z}E(z,t) = iN\alpha(z,t) \quad (2)$$

Where E represents the optical electric field and α the polarisation of the atoms. The treatment here will be classical but because of the linearity of (1,2) the results will hold for quantised fields also. We will consider a pulse entering the medium at $-z_0$, $E(z = -z_0, t) = f_{in}(t)$. At $t = 0$ the detunings of the atoms will be flipped

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($-i\eta z \rightarrow +i\eta z$) and we will show that this leads to an output pulse ($f_{out}(t)$) leaving the medium that is closely related to the input pulse. We do this by first solving equations Equations (1,1) subject to the boundary conditions ($\alpha(z, t \rightarrow -\infty) = 0, E(z = -z_0, t) = f_{in}(t)$). We then solve a version of (1,2) with the sign of the $i\eta z$ term reversed and subject to the boundary conditions ($\alpha(z, t \rightarrow +\infty) = 0, E(z = +z_0, t) = f_{out}(t)$). The output pulse is then determined by matching the two solutions at the point where the detunings are flipped (t=0).

Integrating (1) gives:

$$\alpha(z,t) = +ig\int_{-\infty}^{t} d\tau\, e^{-i\eta z(t-\tau)}E(z,\tau) \tag{3}$$
$$= +ig\int_{-\infty}^{\infty} d\tau\, H(t-\tau)e^{-i\eta z(t-\tau)}E(z,\tau) \tag{4}$$

Fourier transforming this and substituting into (2) and then integrating the result gives

$$E(z,\omega) = F_{in}(\omega)\exp\left[-gN\int_{-z0}^{z} dz'\left(\frac{\delta((\omega+\eta z')/(2\pi))}{2} + \frac{1}{i(\omega+\eta z')}\right)\right] \tag{5}$$
$$= F_{in}(\omega)exp\left[\frac{-gN\pi}{\eta}(H(\omega+\eta z) - H(\omega-\eta z_0)) + \frac{igN}{\eta}\log\left|\frac{\omega+\eta z}{\omega-\eta z_0}\right|\right] \tag{6}$$

Where $H(\cdot)$ is Heaviside step function. It can be seen from (6) that each spectral component in the input pulse gets attenuated by a factor $\exp(-gN\pi/\eta)$ after travelling past the position in the sample where it is resonant with the atoms, as well as getting a phase shift as it travels through the sample. To get an expression for $E(z, t = 0)$ one integrates equation (6) over all ω. We will assume that the bandwidth of the memory is larger that the bandwith of the of the input pulse, that is $\eta z_0 \gg \omega$ for all of the spectral components of the input pulse. This simplification leads to an expression for $E(z, t = 0)$ in the form of a convolution. Fourier transforming with respect to the spatial coordinate leads to the following.

$$E(k,t=0) = -\operatorname{sgn}(k)\beta\left|\frac{k}{\eta}\right|^{-2-i\beta}\Gamma(i\beta)\left(\left|\frac{k}{\eta}\right|\cosh\left(\frac{\pi\beta}{2}\right) + \frac{k}{\eta}\sinh\left(\frac{\pi\beta}{2}\right)\right)f_{in}(-\frac{k}{\eta}) \tag{7}$$

where $f_{in}(k/\eta)$ now denotes the input field at the time $t = k/\eta$ and $\beta = gN/\eta$, $\Gamma(\cdot)$ is the gamma function.

In the same manner we can derive an expression for E subject to the final conditions ($\alpha(z, t \rightarrow \infty) = 0, E(z = z_0, t) = f_{out}(t)$), one gets a similar expression to (7) but in terms of $f_{out}(k/\eta)$. Equating the two and making the substitution $k/\eta \rightarrow t$ lead to,

$$f_{out}(t) = f_{in}(-t)|t|^{2i\beta}\frac{\Gamma(i\beta)}{\Gamma(-i\beta)} \tag{8}$$

Because $|t|^{2i\beta}\Gamma(i\beta)/\Gamma(-i\beta)$ has a modulus of 1 for all t, it can bee seen that the envelope of the output pulse is a time reversed version of the input.

In order to get an exact time reversed copy the deterministic phase shift $|t|^{2i\beta}$ will need to be compensated for. One elegant way of compensating for the phase shift would use two memories in series and with the second memory flipping the detunings from $-\eta z$ to $+\eta z$ rather than from $+\eta z$ to $-\eta z$. The terms $|t|^{2i\beta}$ from each memory would then cancel. Another method would be to use an electro-optic phase shifter driven with the appropriate voltage waveform. For the results shown in Fig. 2 where a value for β of 10/3 was used and where the pulse length was around a quarter the length of the storage time, the total phase shift across the output pulse was less than π.

The Maxwell-Bloch equations (1,2) can be integrated numerically and such simulations agree with the analytical treatment given above. Figure 1 is the results of simulations for the gradient echo carried out using the open source package *xmds* [13].

Preliminary experiments have been carried out in a similar manner to the initial demonstrations of photon echoes produced using controlled inhomogeneous broadening [8]. The most substantial difference was the use of praseodymium rather than europium dopants, which allowed much greater optical depths to be obtained. Light from a highly stabilised dye laser was frequency shifted and gated with acousto-optic modulators

(AOMs) and then steered toward the sample of 0.05 at% praseodymium doped in yttrium orthosilicate. The sample was approximately a 4 mm cube and was held at temperatures in the range 2-4 K. Four electrodes were placed around the sample in a quadrupole arrangement and provided an electric field that varied linearly along the optical path. The electrodes were 1.7 mm diameter rods separated by 8 mm, voltages of approximately ± 5 V were used to broaden the antihole. Heterodyne detection was used to detect the transmitted pulses.

Figure 4 shows experimental traces relevant to the operation of the memory. For the shot presented 49% of the incident light was transmitted straight through the sample and 13% came out as an echo. There was some shot to shot variation in the antiholes created leading to a variation of the efficiency of the echo between the values of 10 and 15%. Because of this the spectral width of the unbroadened antihole and the optical depth were allowed to vary in obtaining the experimental fit to the data. An antihole width of 30 kHz was inferred which comparable to the inhomogeneous broadening in the hyperfine transitions and is what should limit the width.

For each site where praseodymium can sit in the lattice, there is another related to it by inversion. Both orientations were used in this experiment and in order to implement the completely efficient memory only one can be used. This could be achieved by Stark shifting with a homogeneous electric field and then optical pumping but it was not done for this work. The theoretical traces on Fig. 4 take the fact that their are two orientations into account.

From Fig. 4 it can be seen that in order to get efficiencies closer to unity the optical depth would have to be increased which will be possible using longer samples. Simulations suggest that efficiencies greater than 50%, (which are required to beat some metric of classical storage [14]) will be possible with only minor improvements to the setup. The improvements needed would be: shaped pulses to better restrict the bandwidth of the pulses; using only one orientation of the praseodymium ions and an increase of the optical depth by a factor of three.

In conclusion we have proposed a quantum memory for light based on optical gradient echoes. When compared to existing quantum memories based on controlled inhomogeneous broadening the new scheme requires only two atomic levels, it is much easier to implement and relevant to a wider range of systems. Initial experiments show an echo efficiency of 13% and time bandwidth product of around three. This already exceeds the performance of quantum memories based on EIT. The experiments are well described by Maxwell-Bloch simulations and such simulations suggest efficiencies much closer to unity should be possible with only modest improvements to the experiment.

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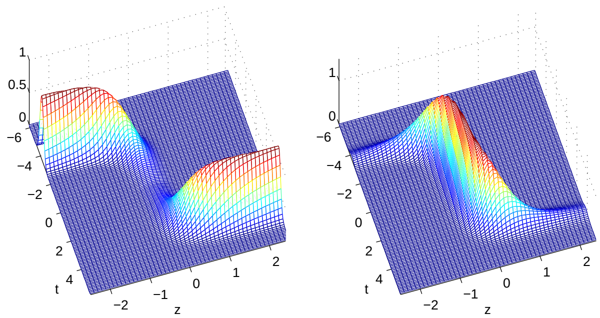

FIG. 1: (Color online) Simulation of the the optical gradient echo showing high efficiency recall of light. The intensity of the light field is shown on the right and the excitation of the atoms is shown on the right. The input pulse which enters the sample at $z = -2.5$ propagates into the crystal and is absorbed, as the pulse travels into the sample it gets narrower in frequency as the various frequency components are absorbed by the sample. For this reason the pulse also stretches temporally as it enters the medium. At t=0 the detunings of the atoms in the sample are flipped and as the atoms rephase they emit an output pulse with the same envelope as the input pulse but reversed in time.

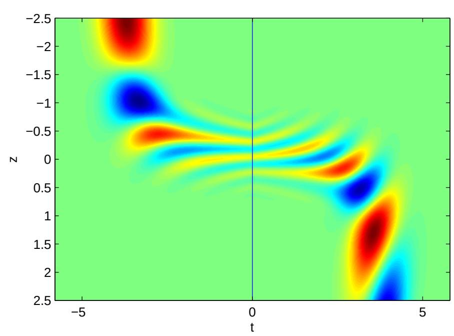

FIG. 2: (Color online) Image map showing the real part of the electric field phasor for the same calculation as Fig 1. The input pulse is in the real quadrature. Although the envelope of the pulse is recreated. The image shows the phase shift across the output pulse. Techniques for cancelling this phase shift are discussed in the text.

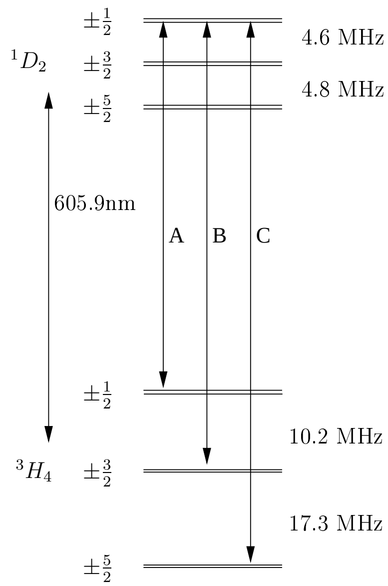

FIG. 3: Energy level diagram for praseodymium dopants in yttrium orthosilicate. The echo is carried out with light at frequency A. To carry out the experiment, the applied light is swept around frequency A to create a spectral hole a few megahertz wide. Then light at frequencies B and C is applied to prepare a narrow antihole at frequency A. Although the diagram here shows the use of the $\pm 1/2$ excited state level, because of the inhomogeneous broadening in the optical transition, there are ions that contribute to the antihole due to the $\pm 3/2$ and $\pm 5/2$ excited states also.

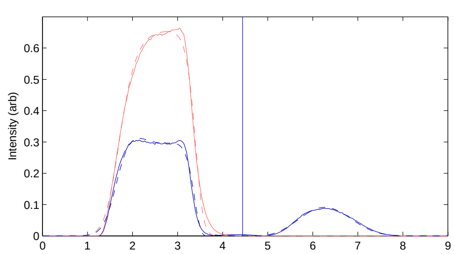

FIG. 4: (Color online) Trace showing experimental gradient echoes and the results of simulations. The solid red (light) line is the pulse that reaches the detector when no antihole is prepared .The dashed red line is what we used as the input to our simulations. The solid blue (dark) line is the experimental trace and the dashed blue line is the simulated result. The vertical line represents the time the Stark shifting electric field was flipped.